The Use of Seismic Refraction Survey in Geotechnical Investigations

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Abstract— *The objective of this project was to use seismic refraction techniques to delineate the subsurface layers as a supplement to routine geotechnical investigations. Seismic velocities of the subsurface material were determined and used to find the possible composition of the subsurface materials and also to delineate the subsurface layers and their thicknesses. The seismic data was obtained using Geometric SmartSeis ST® 12-channel signal enhancement seismograph and Mark Product Limited® 48-Hz geophones. The survey was conducted along four traverse lines each with a length of 135m. It was determined from the seismic survey that the project site maybe underlain by dry loose sand, saturated sand and/or clay material. Information from two exploratory boreholes drilled to a maximum depth of 10.45m at the study area was consistent with the seismic refraction results obtained. The seismic results also showed there could be a fault at the project area along Traverse Line 1 and Traverse Line 2.*

Keywords— ***Boreholes, Geophones, Seismograph, Sesimic velocities, Subsurface.***

I. INTRODUCTION

Geophysics is the science concerned with the study of the physical processes and physical properties of the earth and its surrounding space environment. Although geophysics is mostly applied in geology, it may also be applied in several fields such as civil engineering, hydrology[1]. Geophysics has many disciplines with seismology being the largest, especially in exploration geophysics. Seismology may be either refraction or reflection seismology. Reflection seismology is currently the most commonly used geophysical method in oil and gas exploration even though seismic refraction was the first major geophysical method to be applied in the search of oil bearing structures. Seismic reflection offers a higher degree of technical sophistication in both data acquisition and signals processing even though it provides a 2 or 3 dimensional imagery of the stratigraphic boundaries and geological structures to depths of several kilometers into the earth. It can be used in shallow ground exploration but tend to be relatively expensive compared to electrical resistivity. Refraction seismology measures the arrival times of seismic waves at some fixed positions on the ground after its generation at the focus. For shallow seismic refraction investigations, a small explosive charge or sledge hammer can be used to generate the seismic energy, which moves through the subsurface at a velocity depending on the subsurface material. A part of the waves that travel through the subsurface are refracted at the interface between two layers back to the surface where it is detected by geophones at fixed locations. These signals are then sent to a seismograph which records the arrival times for the signals. The arrival time depends on the velocity of the waves in the layer it travels through and so with the time of arrival and the distance from the focus to the geophone known, the velocity of the wave can be determined. The velocity of a particular earth material can vary over a wide range as a function of its age, its depth of burial, its degree of fracturing or porosity, and whether water or air fills the voids[2]. The velocity variation can also aid in determining the number of layers the wave has travelled through and their elastic properties, thus informing the engineer or geologist on the kind of material to expect at different depths within the subsurface. This research seeks to use the Seismic Refraction Survey method to obtain the subsurface profile for the purpose of geotechnical investigations. Subsurface geotechnical investigations have been used in many cases to determine the properties of the subsurface materials at a site. The results from these investigations inform the engineer on the type and depth of foundation and even the type of excavating equipment to use at the site. Boreholes, trenches and other invasive methods are conventionally used to investigate the subsurface but these are discrete and may cause serious omissions in an attempt to delineate the boundaries of geological structures and the nature of the subsurface. This is a major issue in geotechnical investigation that seismic refraction survey addresses by giving a more continuous information of the subsurface based on which engineering decisions can be made with some degree of certainty. Seismic refraction survey also gives the various layers in the subsurface by using the velocities of the seismic waves in the subsurface thereby helping in reducing the number of borehole that are required for the subsurface investigation at a site. This reduces the cost involved in subsurface investigation. Like all geophysical methods, seismic refraction is non-diagnostic and a specific conclusion of the material making up the subsurface cannot be drawn from the results of the seismic refraction survey alone. It is therefore very important that investigation is supplemented with some boreholes and knowledge of the geology of the area so that the possible material makeup of the subsurface can readily be inferred.

II. GEOLOGY AND PHYSIOGRAPHY OF STUDY AREA

The Kumasi metropolis is underlain predominantly by the middle Precambrian rocks specifically Birimian which comprises of the metasediments and metavolcanics. Also underlying the Kumasi metropolis are the granitoids that intruded and deformed the Birimian rocks [3]. The Kwame Nkrumah University of Science and Technology campus is underlain predominantly by the basin type granitoids. Figure 1 shows the geological setting of the study area. The Kumasi Metropolis falls within the sub-equatorial type with a minimum average temperature of about 21.5◦ and a maximum average temperature of 30.7◦. The average humidity in this area is about 84.16% at 0900GMT and 60% at 1500GMT. The Kumasi city falls within the moist semi-deciduous South-East Ecological zone with tree species such as ceida, triplochlon, celtis and other exotic species. The rich soil promotes agricultural activities generally [4].

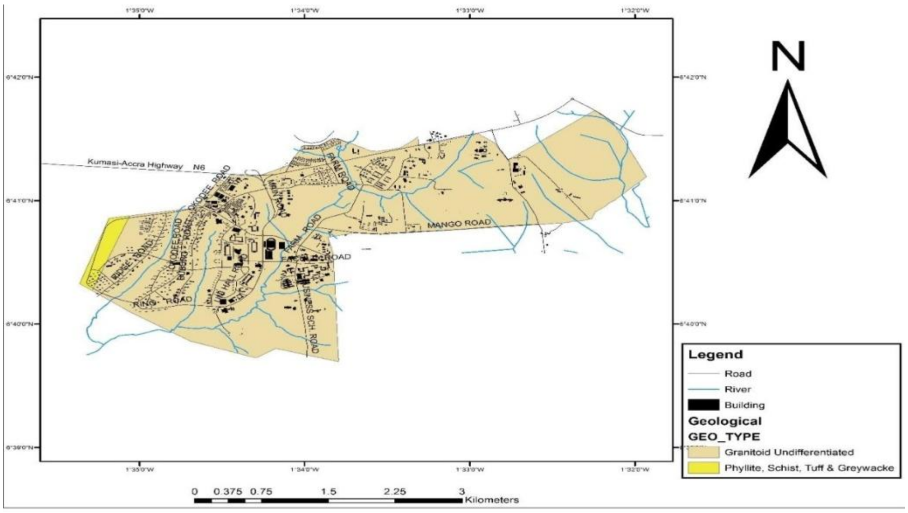


FIGURE 1. Geological Map of Knust

III. FIELD WORK AND DATA PROCESSING

The project was undertaken on the Kwame Nkrumah University of Science and Technology campus at a site in front of the now College of Arts premises. The project site was cleared for development but recently the surface is covered by fresh vegetation and the top soil is sandy material. The site was selected because of ease accessibility and the availability of some geotechnical data from boreholes drilled at the site, which was used to supplement the geophysical information. In order to determine the detailed subsurface profile, two traverse lines (Traverse Line 3 and Traverse Line 4) were chosen along slope and another two traverse lines (Traverse Line 1 and Traverse Line 2) across slope. **Figure 2** shows a plan view of the site with the traverse lines.

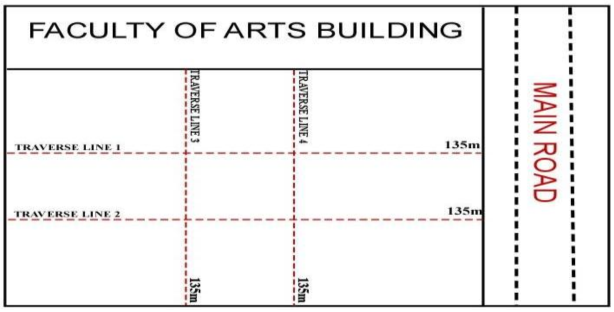


FIGURE 2. Plan View of the Study Area

3.1 Materials and Method Used

The main equipment used was the Geometrics SmartSeis ST-12-channel signal enhancement seismograph and its accessories including Mark Product Limited® 48-Hz geophones and the seismic cables. Also used were a hammer and a metallic plate to generate seismic waves. The SmartSeis ST seismograph has the ability to filter disturbances of different amplitudes which are generated from other activities during the seismic field work other than the main waves generated by the impact. This filtering feature helps in producing clearer seismograms from which the first arrivals can be picked. The seismograph also has the ability to store seismograms allowing access after field work. The SmartSeis ST Seismograph can add up signals in a process called stacking which increase the amplitude of the waves that are generated. Stacking helps improve the signal-to-noise ratio as the ground is struck with hammer repeatedly. This generates clear seismograms from which the first arrivals can be picked. The hammer and metallic plate was used to generate the seismic waves because our investigations were shallow and all the other sources of seismic wave generation are expensive and others (explosives) in addition to been expensive, are very difficult to handle. The 12 geophones used gave a spread of 60m for the survey. The maximum depth of investigation in a seismic survey is estimated to be about one third of the geophone spread; the depth of our investigation is therefore about 20m which exceeds the usual depth of geotechnical investigation (10m). The seismic refraction survey was carried out by first marking the traverse line. The tape measure was spread along each traverse line and the shot points and geophone positions were marked off. For this research, the survey was done along four traverse lines. Two of these traverse lines were along slope and the other two were across the slope. Each traverse line was 135m in length and 6 shots were initiated along each traverse line. A forward shot (0m) and a reverse shot at (65m) and intermediate shots at (20m, 25m, 40m, and 45m). This was to give a better resolution of the subsurface along each traverse line. At the shot point, the sledge hammer was hit on a metal plate to generate the seismic waves. Staking was done twice so as to increase the intensity of the waves. This was repeated for all the shot points on all the traverse lines. The seismograph was used to record and store the seismogram from which the first break was picked. The filter system of the seismograph was used to eliminate noise of different intensities which was generated during the seismic survey.

IV. RESULTS AND DISCUSSION

The seismic survey investigation was conducted along four traverse lines as indicated in the methodology. The first arrival times were obtained from the seismograms that were generated by the SmartSeis ST Seismograph and plotted against the offset distances. The graphs displayed points that fall along distinct lines, the number of distinct lines shows the number of layers detected in the subsurface. The gradients of these lines were used to compute their velocities and thicknesses. **Figure 3** is a typical time-distance graph showing three layers with the equations of the distinct lines.

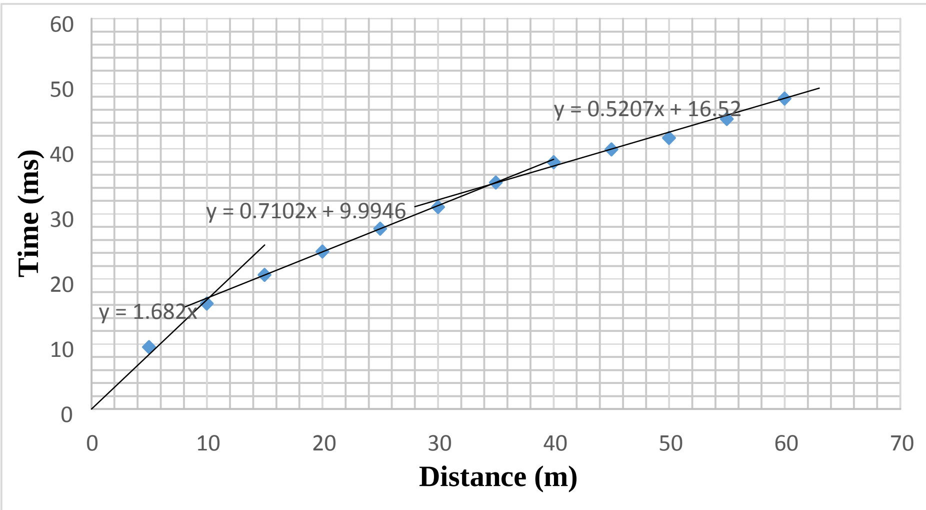


FIGURE 3. Distance Time Graph Obtained For Shot Point 40m along Traverse Line 4

From the graph in **Figure 3**, the velocity of each layer is given by the inverse of the gradient of the line representing that layer. The computations are as shown below:

$$V_1 = \frac{1000}{1.682} m/s = 594.5\ m/s$$

$$V_2 = \frac{1000}{0.710} m/s = 1408.5\ m/s$$

$V_3 = \frac{10000}{0.521}\ m/s = 1912.2$ m/s

$$h_1 = \frac{t_1}{2} \times \frac{v_1 \times v_2}{\sqrt{v_2^2 - v_1^2}} h_2 = \frac{v_2 v_3}{\sqrt{v_3^2 - v_3^2}} \times \left(\frac{t_2}{2} - \frac{h_1 \sqrt{v_3^2 - v_1^2}}{v_1 \times v_3} \right)$$

$$h_1 = \frac{9.9994 \times 10^{-3}}{2} \times \frac{594.5 \times 1408.5}{\sqrt{1408.5^2 - 594.5^2}} = 3.3m$$

$$h_2 = \frac{1408.5 \times 1919.23}{\sqrt{1919.23^2 - 1408.5^2}} \times \left(\frac{16.52 \times 10^{-3}}{2} - \frac{3.3\sqrt{1919.23^2 - 594.5^2}}{594.5 \times 1919.23} \right) = 6.2m$$

TABLE 1
LAYERS DETECTED AT SHOT 40 M ALONG TRAVERSE LINE 4

SP	traverse	Layer	gradient	t_i(ms)	Velocity(m/s)	Thickness(m)
SP 40	Forward	1	1.682	0	594.5	3.3
		2	0.7102	9.995	1408.5	6.2
		3	0.5207	16.52	1919.23	

Based on the estimated velocities and thicknesses of the layers from the time-distance plots, the possible interpretations of the subsurface material and structures, of the study area are presented below.

4.1 Traverse Line 1

Table 6 shows the computation of velocities and thicknesses of the various layers along Traverse Line 1. The Traverse Line 1 reveals three layers with average velocities of 459.1, 1451.6, and 1718.3m/s for the first, second and third layers respectively. The velocities indicate that the first layer may be dry loose sand, the second layer saturated clay material and third layer may be made of saturated clay and sand material. **Figure 4** shows a simplified profile of the subsurface with the thicknesses of the various layers and the dip of the interface between the layers at areas along the Traverse Lines.

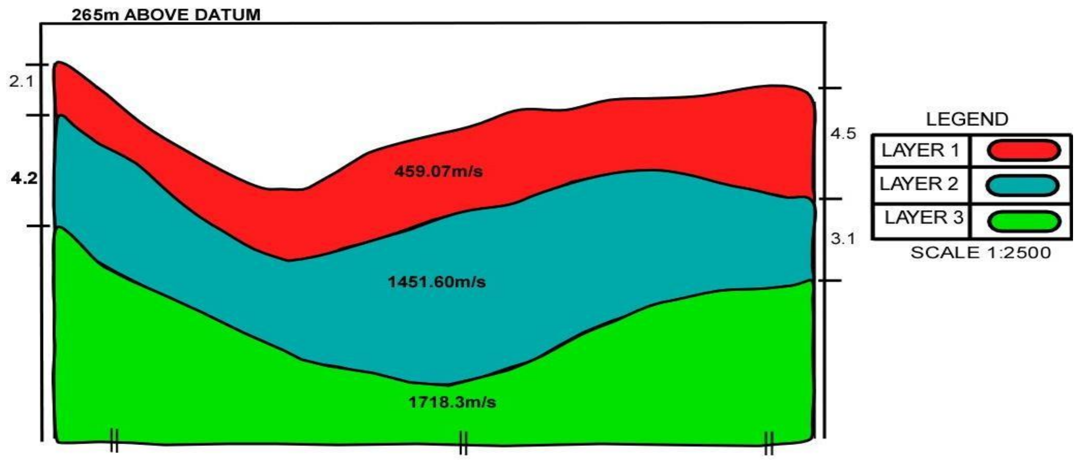


FIGURE 4: Subsurface Model Revealed by Traverse Line 1

4.2 Traverse Line 2

Three layers were realised in the subsurface along Traverse Line 2 with average velocities of 369.6, 1864.0, and 2103.0m/s for the first, second and third respectively as shown in the tabular representation of computations in **Table 7**. From the velocities obtained, the first layer is likely to be dry loose sand, whilst the second and third layers may be saturated clayey sand material with the second layer denser than the third layer. The graphs and the velocities obtained from the forward traverse indicate there may be a fault along this traverse line. **Figure 5** shows the nature of the subsurface with the thicknesses of the various layers and the dip of the interface between the layers at areas along the Traverse Lines.

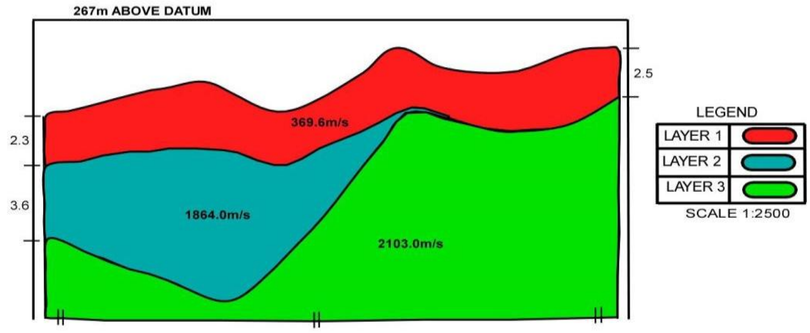


FIGURE 5. Subsurafce Model Revealed by Traverse Line 2

4.3 Traverse Line 3

Shown in **Table 8** is a tabular representation of the computation of velocities and thicknesses of the various layers along Traverse Line 3. Three layers with average velocities 794.6, 1427.2, and 1666.9m/s for layer 1, layer 2 and layer 3 respectively. These velocities indicate that the first layer may be compact sand material, the second layer saturated clay material and the third layer may be saturated clay and sand material. **Figure 6** shows the nature of the subsurface with the thicknesses of the various layers and the nature of the interface between the layers at areas along the Traverse Lines.

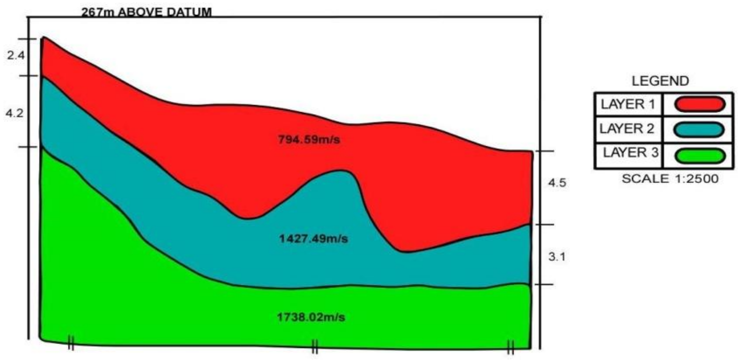


FIGURE 6. Subsurface Model Revealed by Traverse Line 3

4.4 Traverse Line 4

Shown in **Table 9** is a tabular representation of the computation of velocities and thicknesses of the various layers along traverse line 4. The traverse shows three layers with average velocities of 643.7, 1311.0, and 1344.7 m/s for the first, second and third layers respectively. From the velocities obtained, the first layer may be made of compact sand materials, the second and third layer may be saturated clay and sand material. **Figure 7** shows the nature of the subsurface with the thicknesses of the various layers and the dip of the interface between the layers at areas along the Traverse Lines.

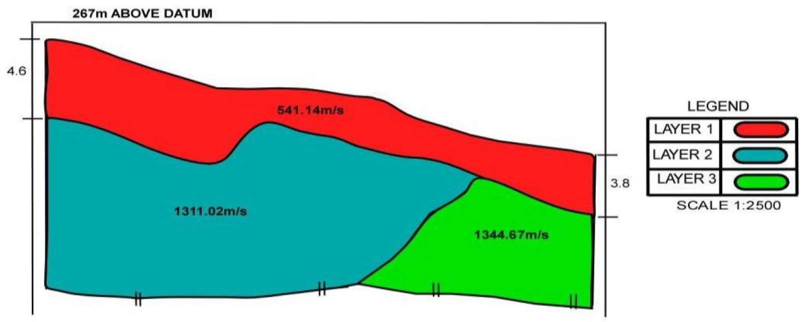


FIGURE 7. Subsurface Model Revealed By Traverse Line 4

V. CONCLUSION

From the analysis of the Time Distance graph, the project site may be underlain by three layers with average seismic velocities of the layers ranging from 369.6 to 2103.3m/s. The project site may therefore be underlain by dry loose sand, saturated sand and clay material. Two exploratory boreholes with a maximum depth of 10.45m have been drilled at the site for investigation and the materials that were obtained from the boreholes are consistent with the materials detected in the subsurface by the seismic survey. Analysis of the graphs, **(Figure 11, Figure 14, and Figure 21)** indicates that there could be a fault at the project site specifically along Traverse Line 1 and Traverse Line 2. From the thicknesses obtained at the various shot points, models of the subsurface were generated as shown in **Figure 4, Figure 5, Figure 6 and Figure 7**. The thickness of the first layer was realized to fall between 2.1m to 7.2m. From the subsurface models, Traverse line 1 reveals three layers with the interfaces between the layers mimicking the topography as shown in the subsurface model in **Figure 4**. Traverse line 2 also reveals three layers with the interface between the first and second layer mimicking the topography along that traverse line. The break which is also detected from the Time Distance graphs **(Figure 14 and Figure 17)** also shows in the model of subsurface along this traverse line shown in **Figure 5**. Traverse Line 3 reveals three layers. The subsurface model as shown in **Figure 6** shows that there could be a fold of the second layer into the first layer making the interface between the first and second layer undulating. The thickness of the second layer reduces down slope (that is from shot point 0m because 65m) along this Traverse Line. The Time Distance graphs shown in **Figure 20, Figure 22, Figure 23**, and **Figure 24** indicate that, at some points along the distinct line representing the second layer, the refracted seismic waves have shorter or longer arrival times. This also shows that interface between the first and second layers could be undulating as shown in the subsurface as shown in the subsurface model in **Figure 6**. Three layers were realised in the subsurface along Traverse Line 4. The interface between the second and third layer is nearly vertical as shown in the subsurface model along this traverse line. The thickness of the first layer reduces down slope (that is from shot point 0m to shot point 65m). This is shown in the subsurface model shown in **Figure 7.**

TABLE 2
FIRST ARRIVAL TIMES MEASURED ALONG TRAVERSE LINE 1

X	SP 0m	SP 20m	SP 40m	X	SP 65m	SP 45m	SP 25m
5	14.05	12.73	11.76	60	47.06	47.76	48.64
10	19.5	18.26	18.7	55	44.42	44.86	46.18
15	23.79	21.33	21.77	50	41.26	41.96	43.54
20	27.74	24.84	25.99	45	39.07	39.33	40.65
25	32.22	28.44	29.76	40	36.87	37.05	38.36
30	35.29	31.96	32.22	35	34.15	33.98	35.99
35	38.19	35.12	34.85	30	31.34	30.64	33.1
40	41.96	37.93	38.63	25	28.44	27.3	30.64
45	45.04	40.65	40.38	20	25.11	24.23	27.3
50	47.32	43.28	45.48	15	22.04	20.89	23.79
55	50.57	46.62	49.51	10	18.7	17.38	20.02
60	54.61	50.57	55.92	5	10.89	11.33	12.03

TABLE 3
FIRST ARRIVAL TIMES MEASURED ALONG TRAVERSE LINE 2

X	SP 0m	SP 20m	SP 40m	X	SP 65m	SP 45m	SP 25m
5	13.61	14.66	13.25	60	40.38	41.26	41.7
10	18	20.02	19.58	55	38.63	39.51	39.77
15	20.02	23.09	22.47	50	36.43	37.49	37.49
20	21.6	26.25	26.25	45	32.66	34.15	35.12
25	23.97	28.88	29.32	40	30.9	31.52	32.66
30	26.86	31.52	32.66	35	28.88	29.06	29.76
35	29.5	34.15	35.73	30	27.13	26.86	28.01
40	31.96	36.87	38.36	25	24.84	23.97	25.28
45	33.98	38.89	39.95	20	22.21	21.6	23.35
50	35.99	40.65	42.58	15	20.02	19.31	20.19
55	38.19	42.4	45.74	10	17.82	16.68	17.82
60	41.26	45.04	48.81	5	13.5	12.2	14.22

TABLE 4
FIRST TIMES ARRIVAL MEASURED ALONG TRAVERSE 3

X	SP 0m	SP 20m	SP 40m	X	SP 65m	SP 45m	SP 25m
5	10.71	7.81	8.25	60	53.29	51.45	47.5
10	17.38	13.75	14.25	55	49.69	47.32	44.16
15	20.89	18.88	20	50	46.18	43.11	41.09
20	24.67	21.33	23.97	45	42.84	39.95	39.33
25	29.32	24.64	29.5	40	39.51	37.93	36.87
30	33.1	27.57	35.99	35	35.99	35.56	34.41
35	35.99	30.46	40	30	31.96	32.22	31.52
40	38.36	33.1	42.84	25	26.43	28.44	28.62
45	39.95	35.73	45.5	20	22.75	24.84	25.28
50	42.58	37.75	48.64	15	16.25	20.02	21.33
55	45.91	40.38	53.03	10	10.25	14.25	15.25
60	48.64	43.04	56.36	5	5.75	8.5	8.25

TABLE 5
FIRST TIME ARRIVAL MEASURED ALONG TRAVERSE LINE 5

X	SP 0m	SP 20m	SP 40m	X	SP 65m	SP 45m	SP 25m
5	13	10.71	9.57	60	61.89	54.78	53.03
10	19.5	18	16.24	55	56.36	50.83	48.64
15	26.86	24.41	20.63	50	51.27	46.18	44.87
20	31.78	29.76	24.23	45	46.18	43.72	41.53
25	36.43	34.15	27.74	40	41.7	40.82	38.36
30	39.51	37.75	31.08	35	38.63	37.93	35.12
35	43.11	40.21	34.85	30	35.12	34.15	31.78
40	47.06	43.98	37.93	25	31.34	29.76	28.18
45	50.39	48.2	39.95	20	26.86	25.81	24.41
50	54.34	51.97	41.7	15	22.47	21.33	20.89
55	58.56	55.22	44.6	10	16.86	16.68	16.86
60	64.35	59	47.76	5	11.33	10.27	11.59

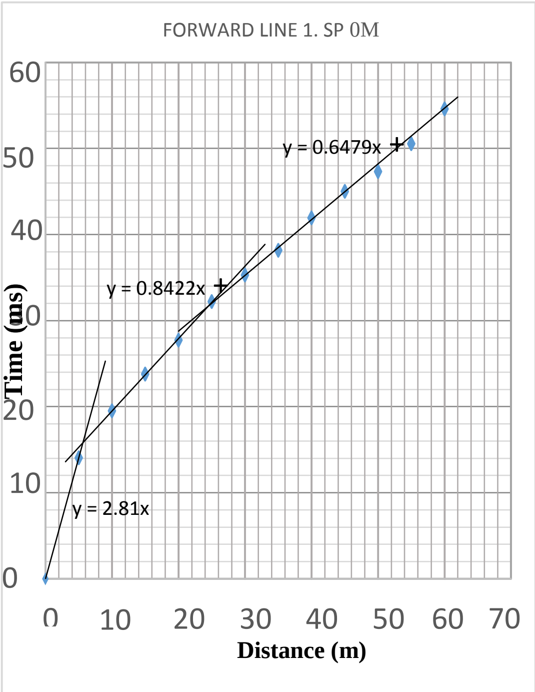
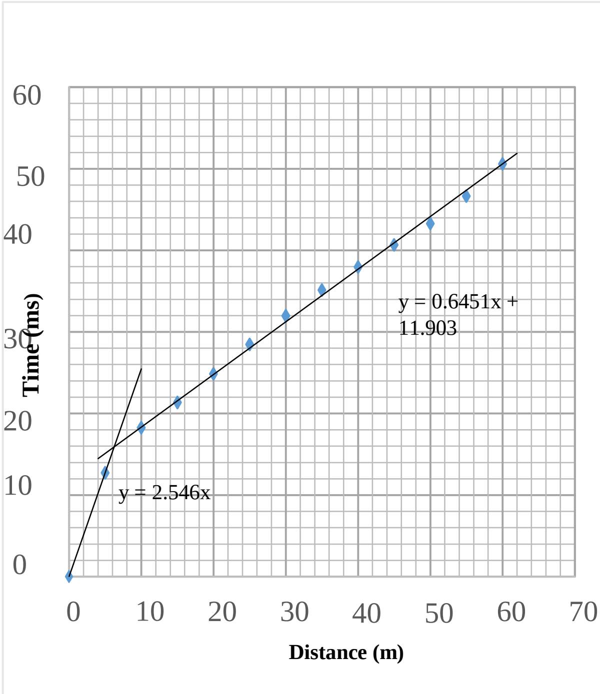


FIGURE 8



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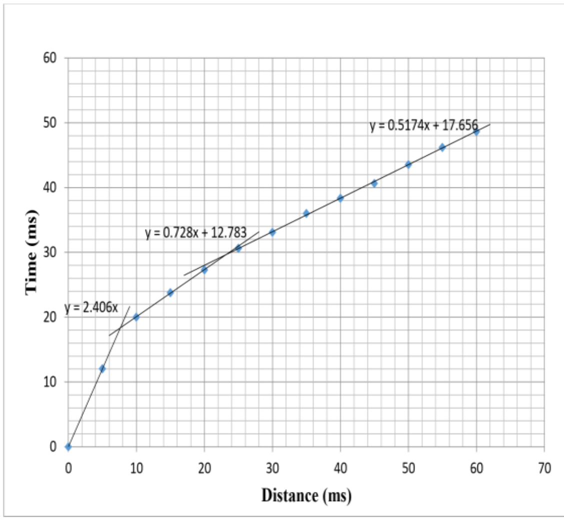

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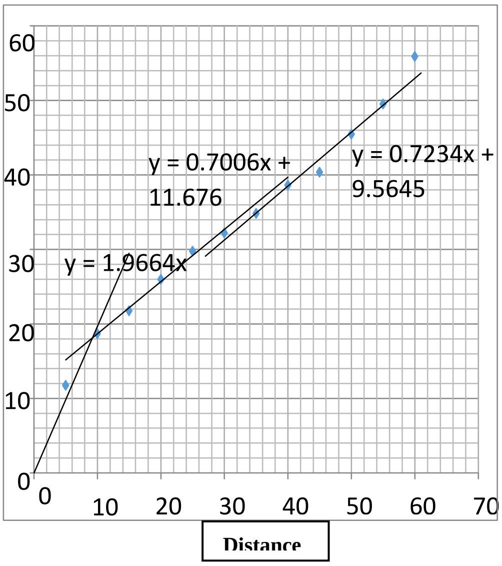

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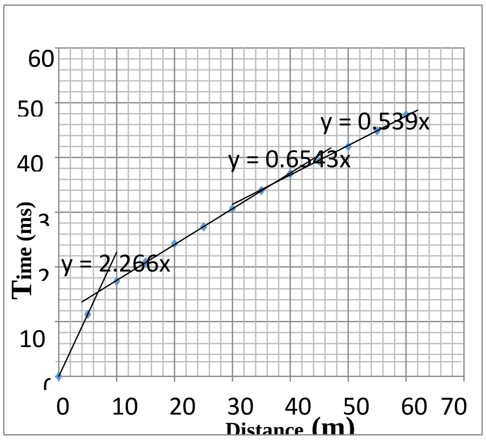

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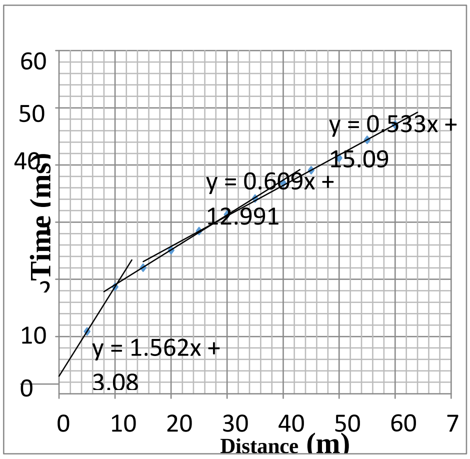

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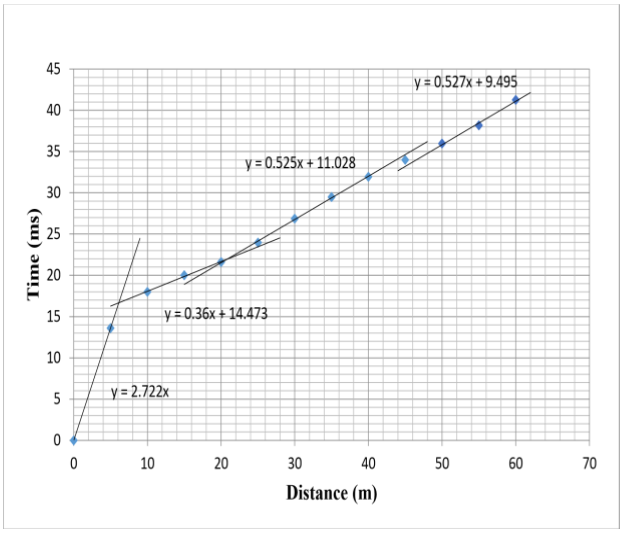

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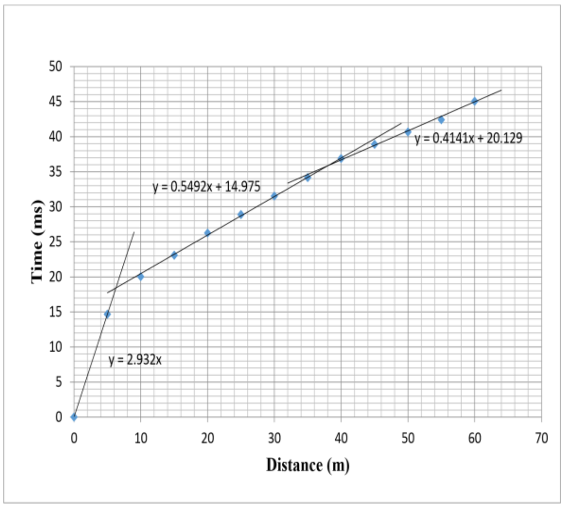

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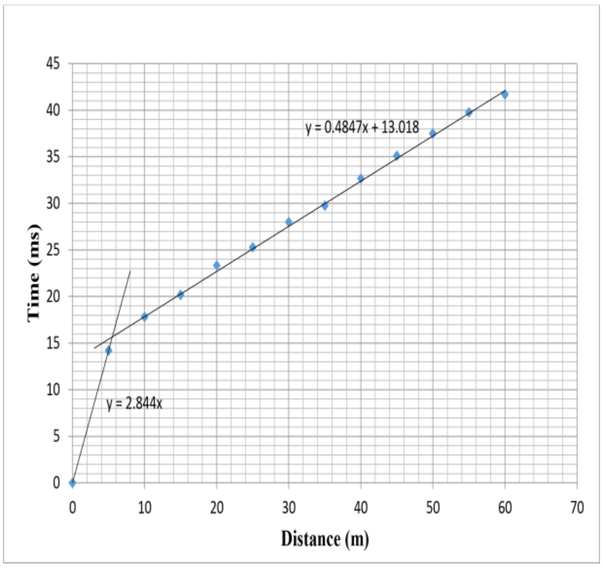

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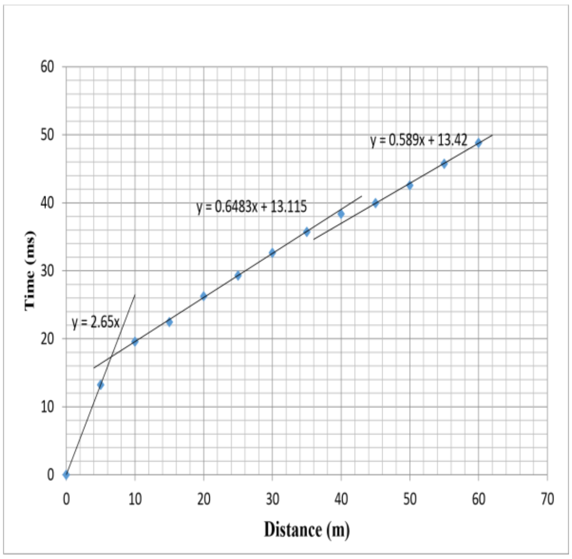

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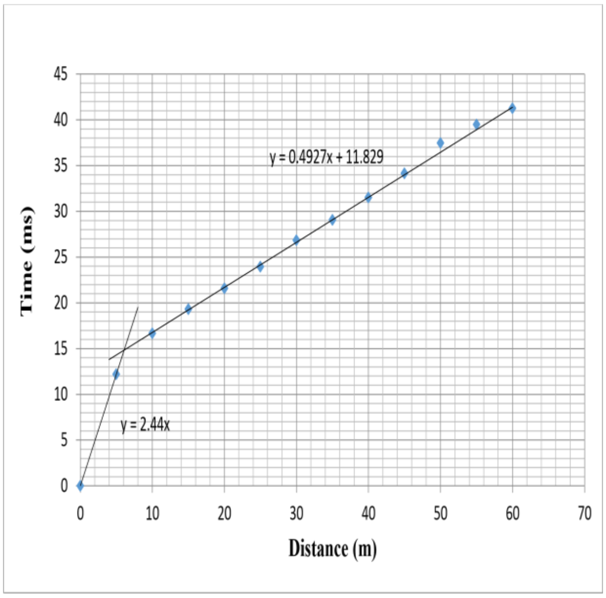

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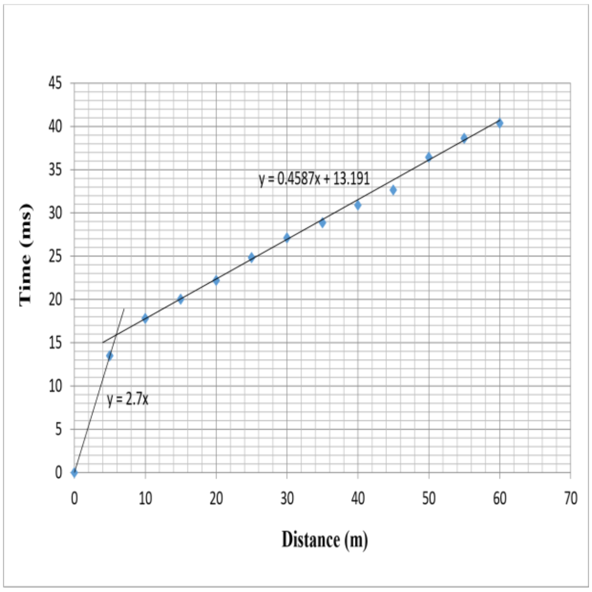

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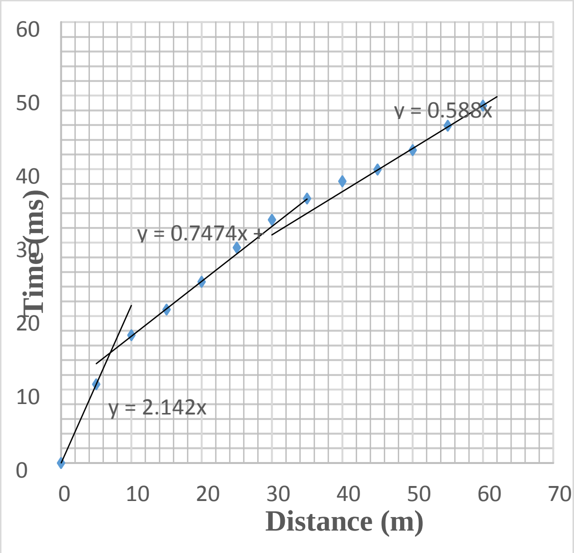

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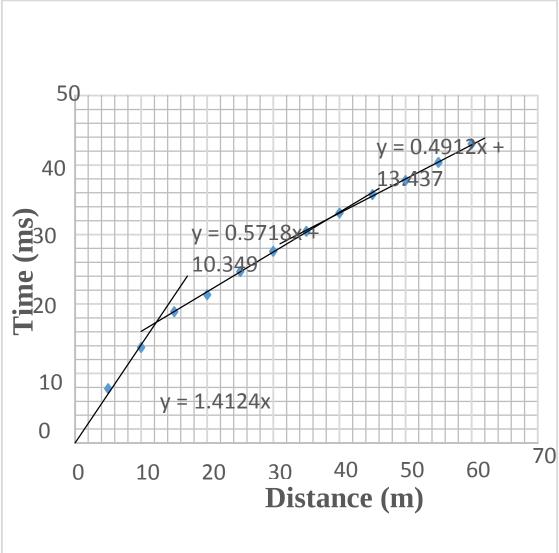

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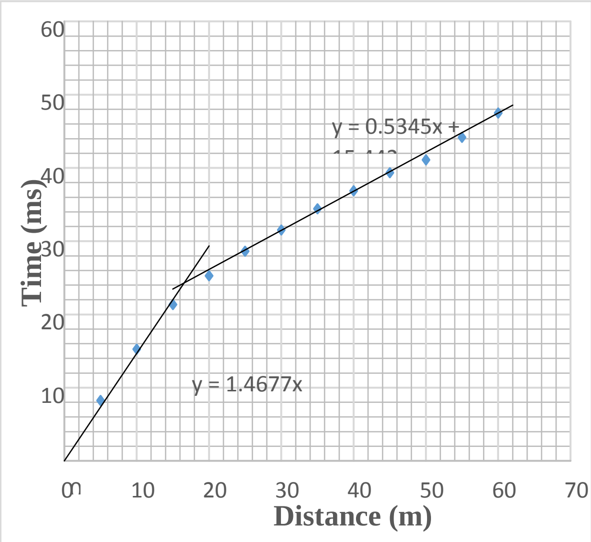

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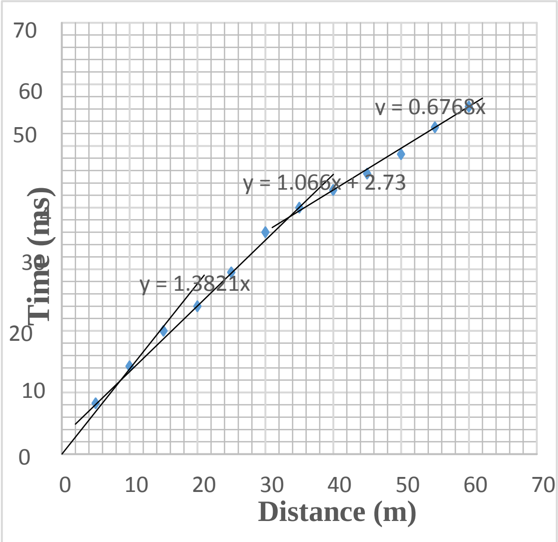

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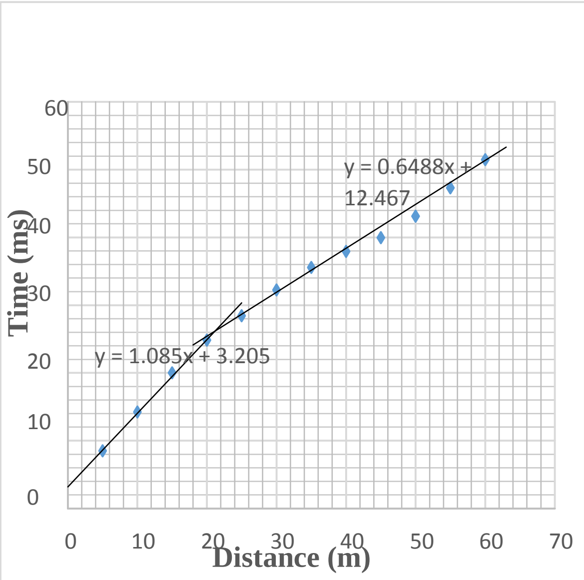

FIGURE 24

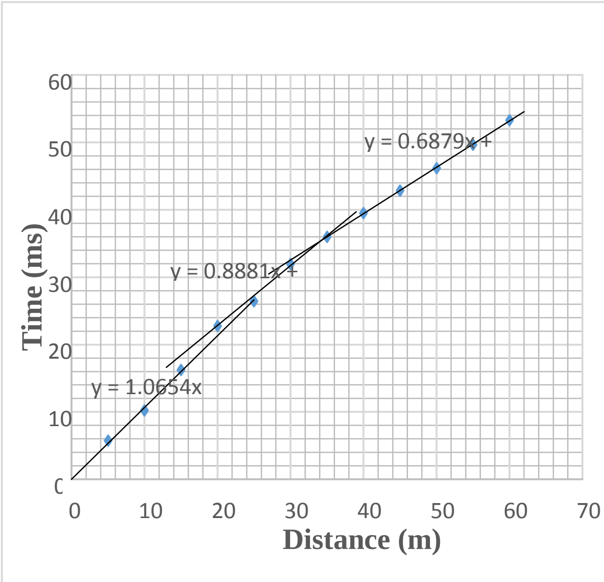

FIGURE 25

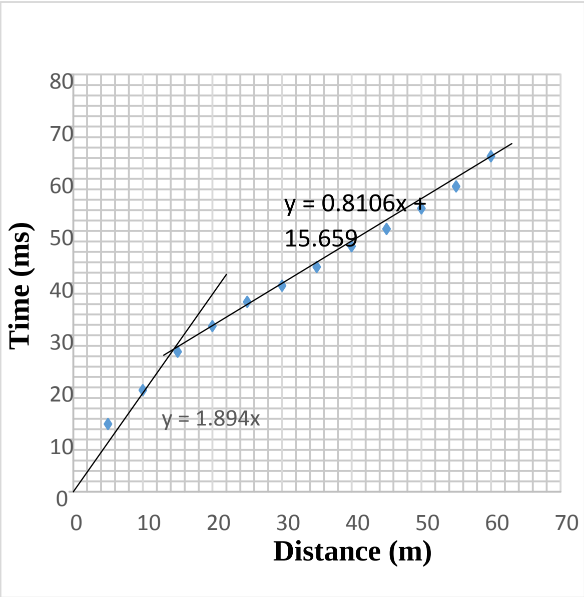

FIGURE 26

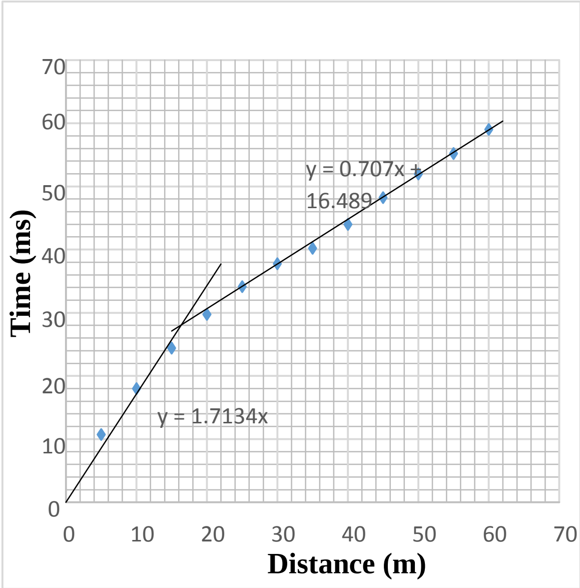

FIGURE 27

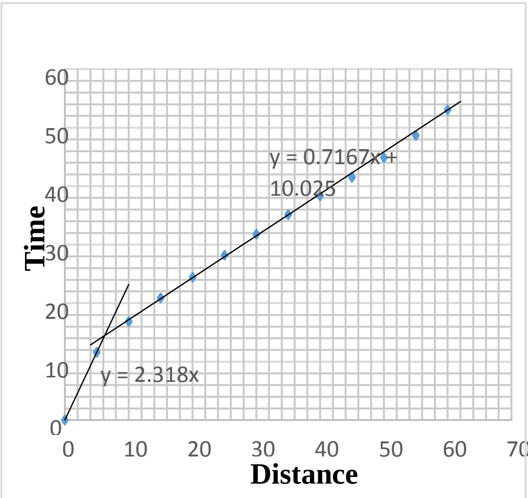

FIGURE 28

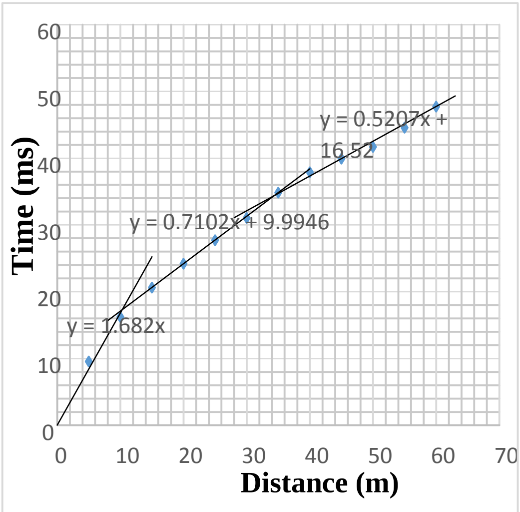

FIGURE 29

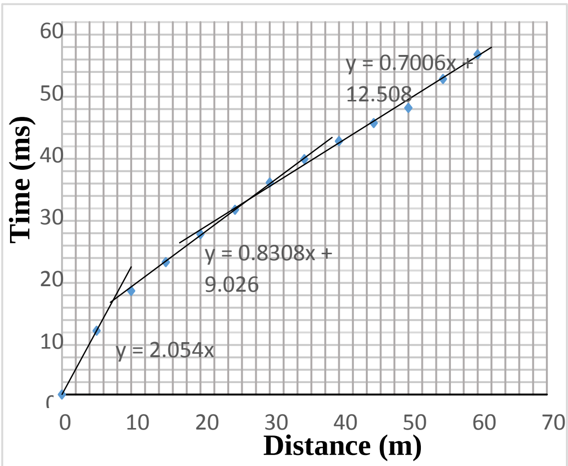

FIGURE 30

FIGURES 8-30: Show Distance Time Graphs Obtained For Shot Points 0 To 65m Each For The Traverse Lines

TABLE 6
SEISMIC COMPUTATIONS FOR TRAVERSE LINE 1

SP(m)	Traverse	Layer	Gradient	ti(ms)	V (m/s)	Thickness(m)	V_{avg}(m/s)
0	Forward	1	2.81	0	355.87	2.1	459.07
		2	0.8422	11.074	1187.37	4.2	1451.60
		3	0.6479	15.808	1543.45		1718.30
20	Forward	1	2.546	0	392.77	2.4	
		2	0.6451	11.903	1550.15		
25	Reverse	1	2.406	0	415.63	2.8	
		2	0.728	12.780	1373.63	4.4	
		3	0.517	17.650	1934.24		
40	Forward	1	1.966	0	508.65	3.2	
		2	0.7006	11.676	1427.35		
		3	0.7234		1382.36		
45	Reverse	1	2.266	0	441.31	2.5	
		2	0.654	10.990	1529.05	5.5	
		3	0.539	15.240	1855.29		
65	Reverse	1	1.562	0	640.20	4.5	
		2	0.609	12.990	1642.04	3.1	
		3	0.533	15.090	1876.17		

TABLE 7
SEISMIC COMPUTATIONS FOR TRAVERSE LINE 2

SP(m)	Traverse	Layer	Gradient	ti(ms)	V (m/s)	Thickness(m)	V_{avg}(m/s)
0	Forward	1	2.722	0	367.38	2.3	369.60
		2	0.493	12.09	2027.99	3.6	1863.96
		3	0.456	13.47	2192.02		2103.00
20	Forward	1	2.932	0	341.06	2.6	
		2	0.549	14.97	1821.49	7.0	
		3	0.414	20.12	2415.46		
25	Reverse	1	2.844	0	351.62	2.3	
		2	0.485	13.018	2063.13		
40	Forward	1	2.650	0	377.36	2.6	
		2	0.648	13.11	1543.21	0.4	
		3	0.589	13.42	1697.79		
45	Reverse	1	2.440	0	409.84	2.5	
		2	0.493	11.829	2029.63		
65	Reverse	1	2.700	0	370.37	2.5	
		2	0.459	13.191	2180.07		

TABLE 8
SEISMIC COMPUTATION FOR TRAVERSE LINE 3

SP(m)	Traverse	Layer	Gradient	ti(ms)	V (m/s)	Thickness(m)	V_{avg}(m/s)
0	Forward	1	2.142	0	466.85	2.4	794.59
		2	0.747	9.784	1337.97	3.6	1427.19
		3	0.588	13.4	1700.68		1666.94
20	Forward	1	1.188	0	841.75	5.0	
		2	0.572	10.349	1748.86	4.6	
		3	0.491	13.437	2035.83		
25	Reverse	1	1.308	0	764.53	6.5	
		2	0.535	15.442	1870.91		
40	Forward	1	1.175	0	851.06	2.8	
		2	1.066	2.73	938.09	6.4	
		3	0.677	15.777	1477.54		
45	Reverse	1	1.085	0	921.66	7.2	
		2	0.649	12.467	1541.31		
65	Reverse	1	1.085	0	921.66	4.1	
		2	0.888	5.0693	1126.00	4.5	
		3	0.688	11.909	1453.70		

TABLE 9
SEISMIC COMPUTATION FOR TRAVERSE LINE 4

SP(m)	Traverse	Layer	Gradient	ti(ms)	V (m/s)	Thickness(m)	V_{avg}(m/s)
0	Forward	1	1.894	0	527.98	4.6	541.14
		2	0.8106	15.659	1233.65		1311.02
		3	0.9307		1074.46		1344.67
20	Forward	1	1.713	0	583.77	5.3	
		2	0.707	16.489	1414.43		
25	Reverse	1	2.318	0	431.41	2.3	
		2	0.7167	10.025	1395.28		
40	Forward	1	1.682		594.53	3.3	
		2	0.71	9.995	1408.45	6.3	
		3	0.521	16.52	1919.39		
45	Reverse	1	2.054	0	486.85	2.4	
		2	0.8308	9.026	1203.66	3.6	
		3	0.7006	12.507	1427.35		
65	Reverse	1	1.607	0	622.28	3.8	
		2	0.826	10.457	1210.65		
		3	1.0444	0.9725	957.49		

VI. RECOMMENDATION

The occurrence of the fault in the study area, specifically along Traverse Line 1 and Traverse Line 2, should be investigated and considered in foundation design since it can result in differential settlement of structures. From our investigation, bedrock may not be encountered at the depth of investigation (approximately 20m). Excavations (commonly not more than 10m) at the site for geotechnical purposes can be done with the appropriate excavators like Tracked or Wheeled excavator or even a Backhoe.

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